Reactor Based Transmutation Studies

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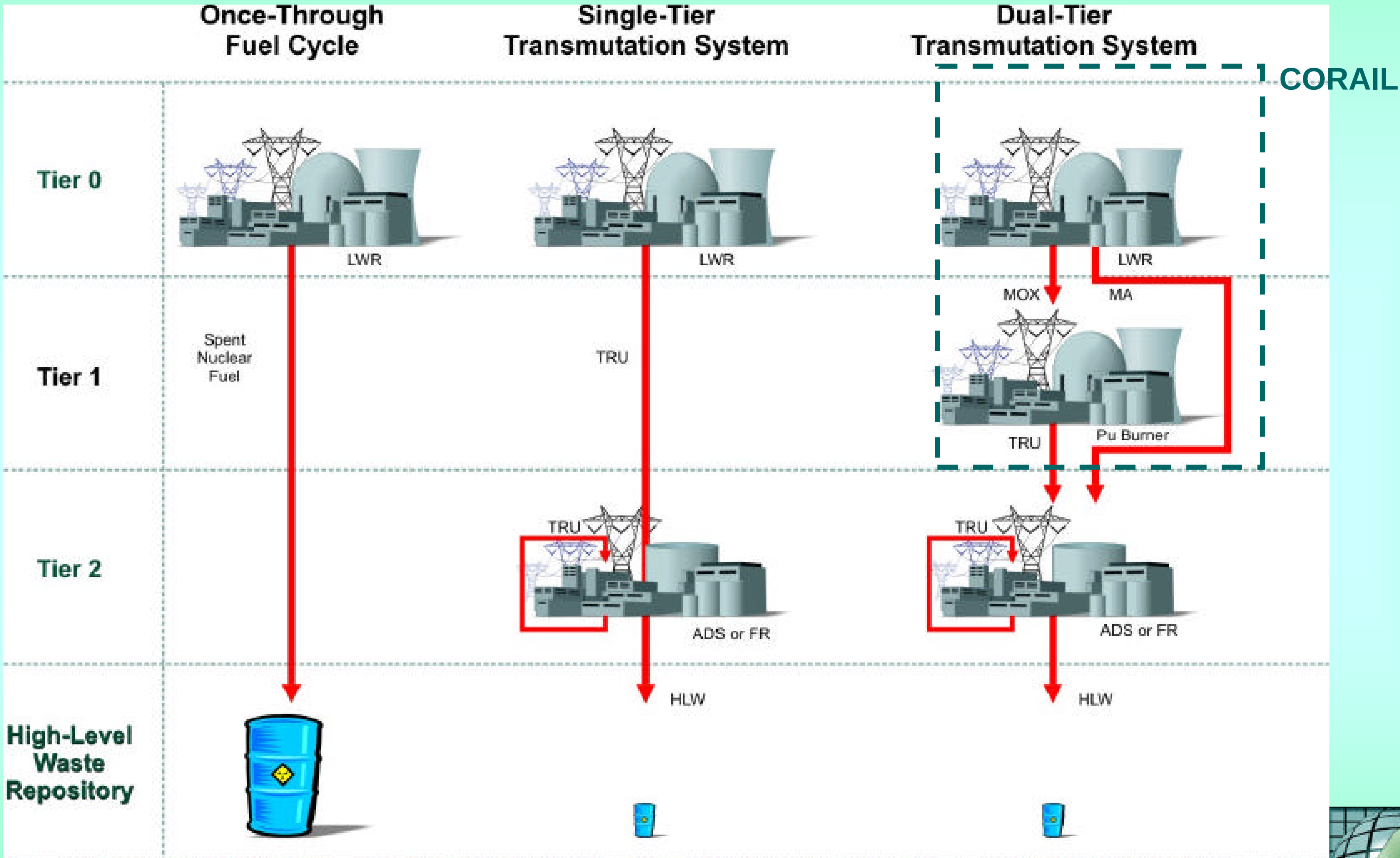
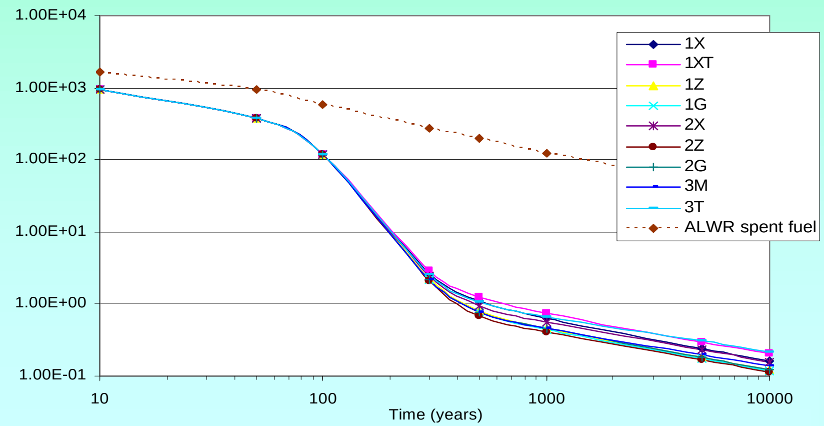
Argonne National Laboratory

Transmutation System Approach

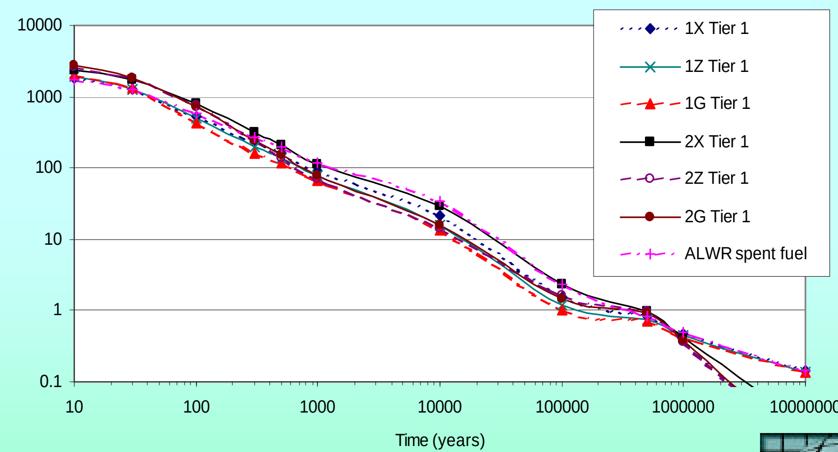


Key Conclusions from Initial Multi-Tier Fuel Cycle Study

- Given clean fuel processing (0.1% losses), typical goals for transmutation can be achieved
  - TRU and plutonium losses to waste less than 0.6%
  - Radiotoxicity below level of natural ore in < 1,000 years
- First tier thermal spectrum irradiation does not significantly reduce the radiotoxicity
  - Confirms need for a final tier fast spectrum system
- Utilization of first tier thermal spectrum system can increase the Tier 2 support ratio
  - Fewer specialized transmutation systems required



Double Tier Irradiation

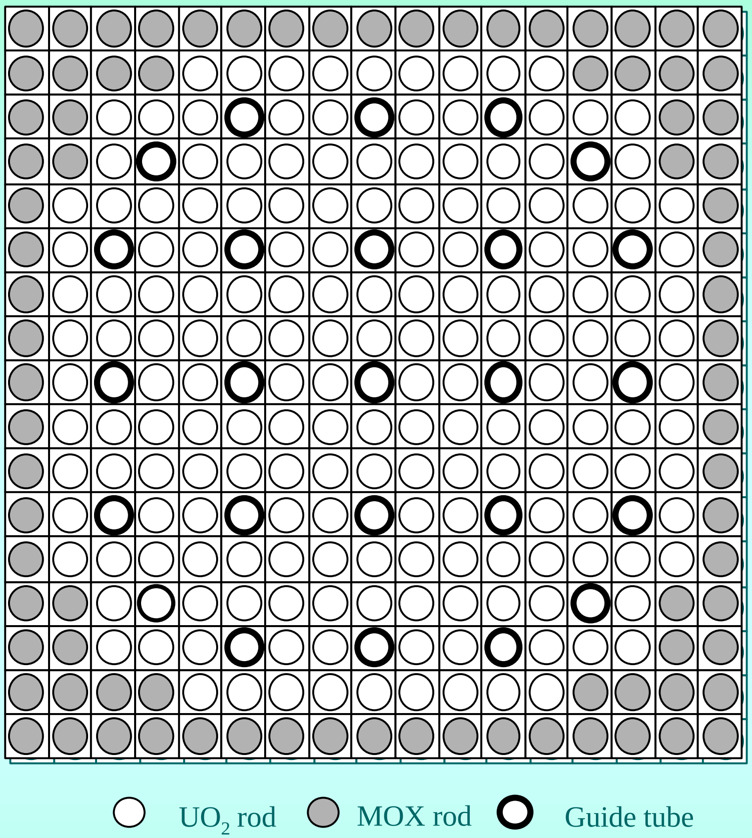


First Tier Irradiation Only

Refined System Studies

- **Potential to achieve deeper burnup in Tier 1 system - ANL**
  - Work has focused on the French CORAIL concept
  - Evaluation of practicality issues
- **Refinement of systems evaluation techniques - LANL**
  - Dynamic analyses of fuel cycle systems
- **Reactor-based transmutation studies**
  - Proliferation resistant LWR fuel cycles – ANL, BNL, MIT
    - MOX, thorium, and nonfertile fuel options
  - Dedicated fast reactor systems – ANL, MIT, U. Mich.
    - Low conversion ratio, heavy metal cooled, and thorium options
  - Long-lived fission production transmutation – ANL
    - Potential in both LWR and FR evaluated

CORAIL Multi-Recycle Concept for Plutonium Stabilization



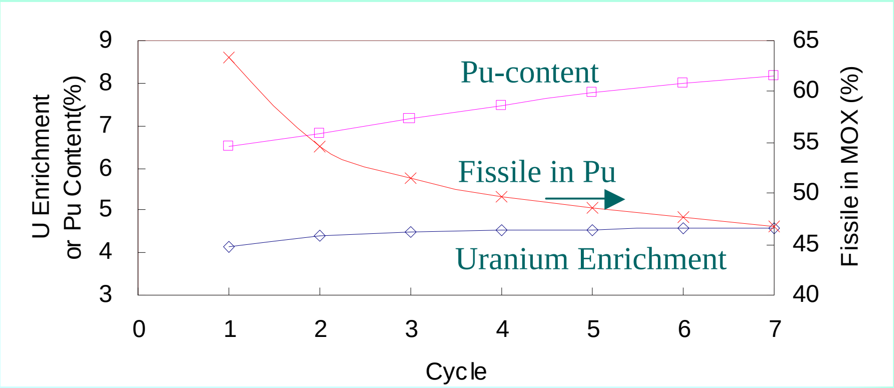
French-CEA CORAIL concept considered for Pu stabilization (i.e., no net production of Pu)

Compatible with existing LWR

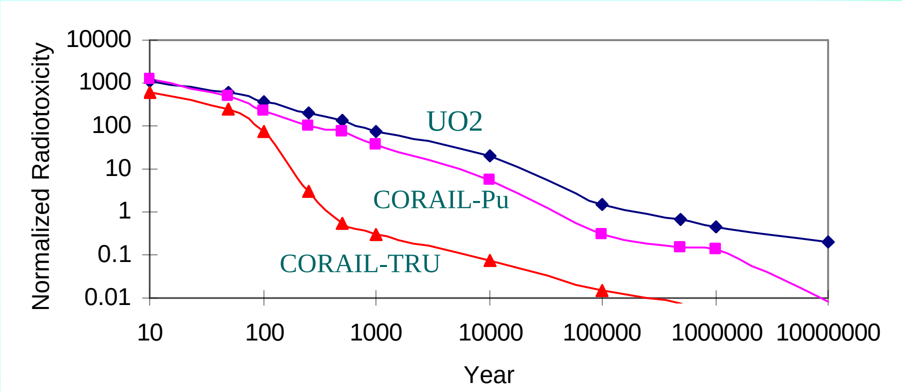
- **Concept**
  - **Heterogeneous assembly in a homogeneous core**
  - **Standard design using fuel rods and assembly that are qualified**
    - **Mass balance in CORAIL core is similar to 30% MOX case, but much better for multirecycling**
  - **Pu/TRU discharged from both MOX and UOX pins is recycled**
- **Design Criteria**
  - **Uranium enrichment < 5.0%**
  - **Pu content in MOX < 12%**
  - **Power peaking factor < 1.2**
  - **No adverse effect on reactivity coefficients and shutdown margin**

Transmutation Performance of CORAIL-Pu Concept

- **No significant degradation of reactivity coefficients with multiple recycle**
- **30% MOX reaches equilibrium Pu isotopics within a few stages**
- **Solution required for minor actinides (MA)**
  - MA content higher than for UO_2 assembly (~3)
  - Direct disposal results in slight reduction of long-term radiotoxicity
  - Dual tier strategy sends minor actinide as fuel to Tier 2
- **Supporting studies pursued**
  - Detailed comparison of power distributions with CEA results



Mass Evolution with Recycling (CORAIL-Pu)



Normalized Cancer Dose

Impact of CORAIL-Pu Deep Burnup on Tier 2 ADS Performance

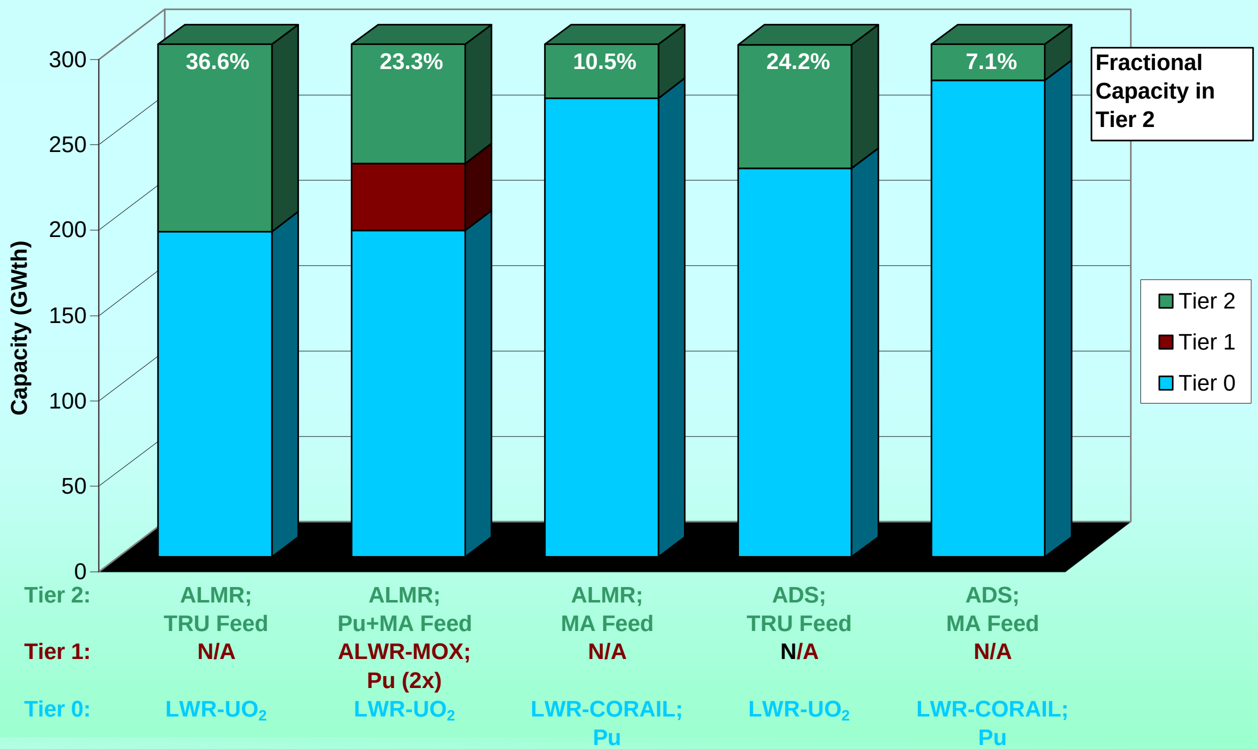
- **Extent of burnup in Tier 1 impacts Tier 2 performance**
  - Deep burnup results in high minor actinide and low fissile contents
- **Tier 2 fuel inventory is high because of low fissile content**
- **For same energy requirement, the discharge burnup is lower**
  - More processing required to consume material
- **Improved burnup swing because of low fissile content**
- **Effective consumption of 75% of TRU in Tier 1**
  - Reduces Tier 2 support fraction requirements

Parameter	Single Tier ADS	CORAIL ADS
BOEC Heavy metal inventory (kg)	2709	**3848**
Discharge burnup (MWd/kg)	273	**199**
Burnup reactivity loss (%Δk)	4.14	**1.23**
Effect TRU mass reduction in first tier	n/a	~75%

LWR Recycle Reduces Tier 2 Capacity

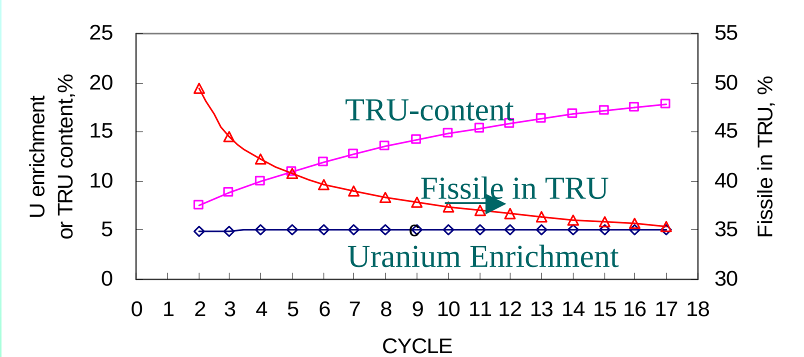
- **Downselection studies focused on "deep burnup" of TRU in commercial sector by utilizing CORAIL concept**
  - Pu multi-recycling stabilizes Pu; only minor actinides are sent to transmutation sector (conversion ratio ADS=0.0; fast reactor~0.5)

Thermal Power Capacity by Tier in a Sustained Nuclear Enterprise
(300 GWth Enterprise includes Commercial and Transmutation Sectors)

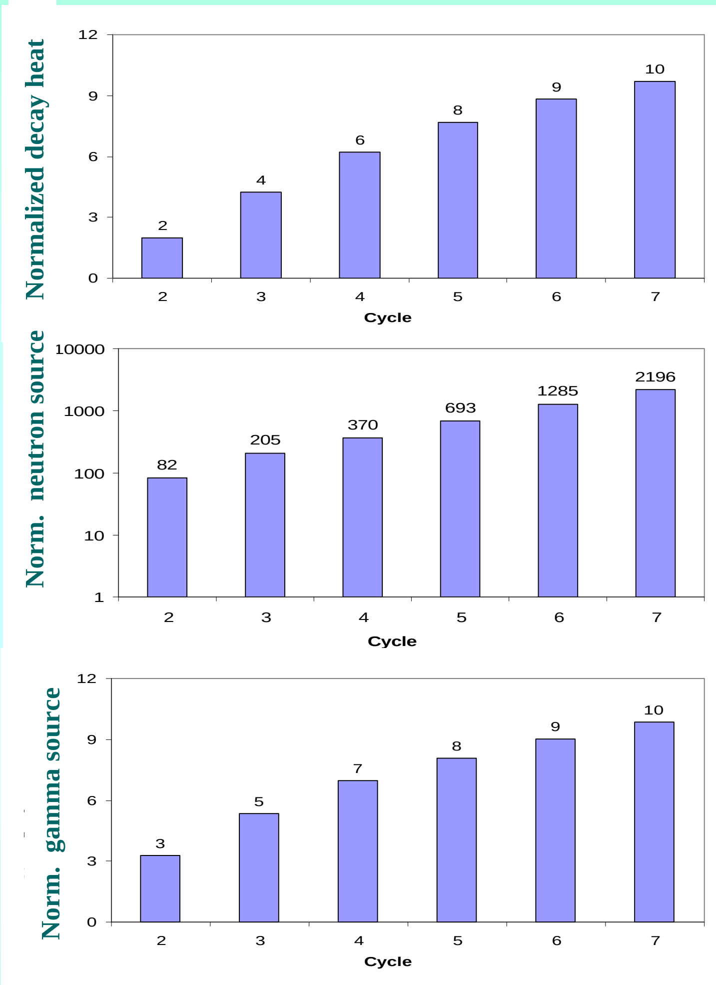


CORAIL-TRU Multi-recycling Results Less Convincing

- From physics perspective, repeated recycle can be achieved
- TRU content gradually increases with recycle stage; power peaking a problem at high enrichment
- Alternate assembly designs have been investigated
- High minor actinide content complicates fuel handling; radiation sources and doses evaluated
- Practical considerations likely limit to a few recycles



Mass Evolution with TRU Recycling



Fuel Handling Indices at Fabrication Stage Compared to CORAIL-Pu Cycle 7

Advanced LWR-Based Transmutation of Waste

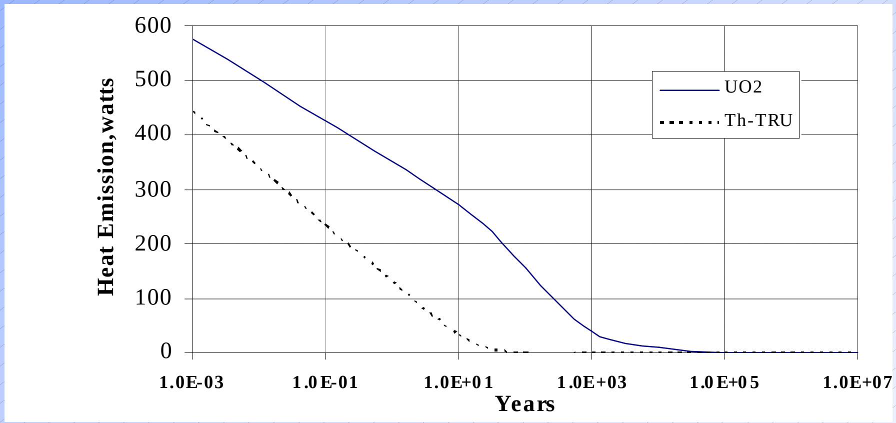
- **Evaluation of proliferation resistant fuel cycles for transmutation of transuranics, using existing or slightly evolutionary LWRs**
  - Assess practical limits of approaches in terms of technological development needs, infrastructure requirements, reactor safety, worker and population dose, and economic issues
  - Propose potential solutions for alleviating limitations
- **Three technologies investigated: MOX, non-fertile, and thorium-based fuel cycles**
  - Different recycle hypotheses using MOX fuel evaluated at ANL
  - BNL investigated the use of Thorium-based fuel
  - Non-fertile fuel form for waste transmutation studied by MIT
- **Results indicate that TRU stabilization approach is more attractive than once-through burner**
  - Fuel handling issues limit number of recycles

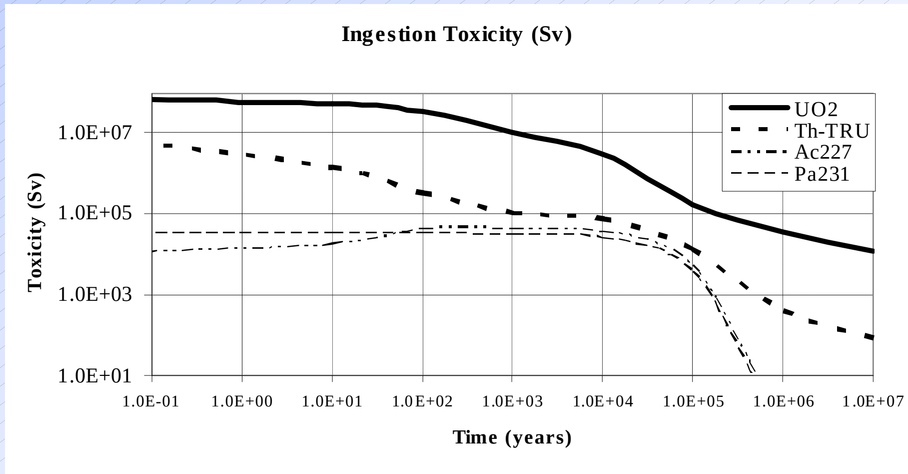
LWR Recycle Hypotheses at Equilibrium States

Recycle Hypothesis	Advantages	Disadvantages
Pu-only	Easiest to implement. Pu out of repository. Reduction in mid-term waste radiotoxicity and heat load.	Pu in fuel cycle needs safeguards (non-proliferation concerns). Radiotoxicity target unmet.
TRU	Clear benefits to repository. Provides time for advanced Series 2 systems to be deployed.	Fuel handling issues in fuel cycle. Limited recycles?
Pu+Np	Similar benefits to Pu-only case. With irradiation, Np-237 and a higher Pu-238 content provides marginal intrinsic radiation sources.	Does not significantly reduce Np-237 in repository. Radiotoxicity target unmet. Similar proliferation issues as Pu.
Pu+Np+Am (PNA)	Removal of Am-241 helps in the mid- and long-term (Np-237 minimized).	Presence of curium limits benefits to the repository (Pu-240 content) Fuel handling is a problem.
PNA and No Pu-242 or Pu242/Am-243)	Radiotoxicity improved over PNA. Provides additional benefits to fuel handling over PNA.	Radiotoxicity target unmet.

LMR Transmutation Scenarios with Th-Fuel

- Two options evaluated
  - Burner - Initial loading from spent LWR TRU + ThO_2; multiple re-cycles performed with additional LWR spent fuel TRU as sole fissile feed.
  - Sustainability – Same initial fuel loading as burner, but subsequent recycles include the TRU and U-233 from previous Th-fuel cycle, supplemented by $(LEU)O_2$.
- Burner transmutation performance
  - Consumes ~25 kg-TRU/assembly/cycle
  - Sharp reduction in boron worth
  - Positive MTC at third recycle
- Sustainable transmutation performance
  - TRU balance after 4 recycles
  - Reduced boron worth, but
  - Fuel and MTC typical
  - Significant reduction in decay heat and toxicity, as shown in figures





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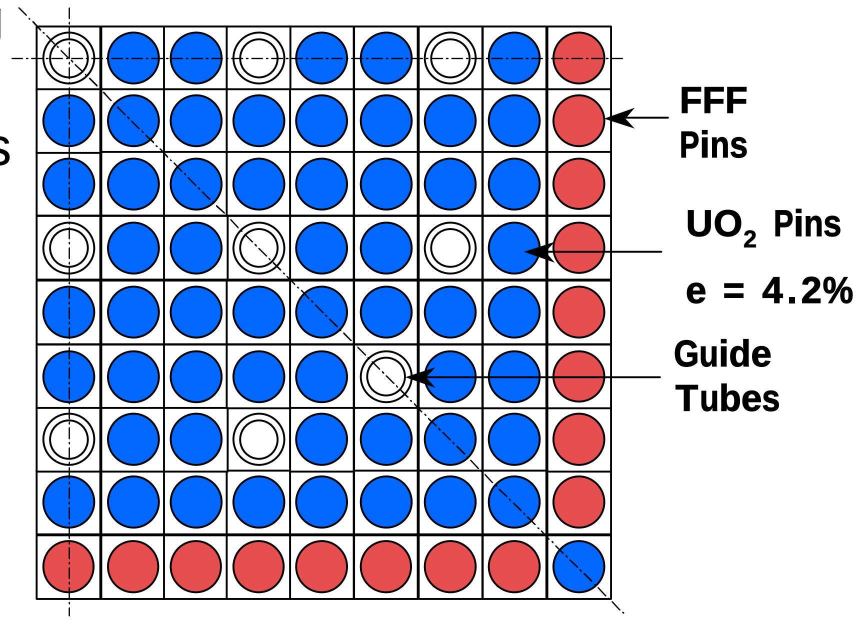
Sustainable Fuel Cycle Results - MIT

Combined **N**on-**F**ertile and **U**ranium Assembly

CONFU

- Equilibrium state with zero net TRU generation while maintaining acceptable reactivity control and thermal hydraulic characteristics possible
- Impact on the environment is limited by 0.1% of reprocessing losses
- Number of recycle stages is constrained by cost and capabilities of fuel reprocessing, handling, and fabrication technologies



- Key challenge - accumulation of Cf and Cm isotopes, which complicates reprocessing and fabrication due to high SFS

Advanced Fast Reactor (FR) Based Transmutation of Waste

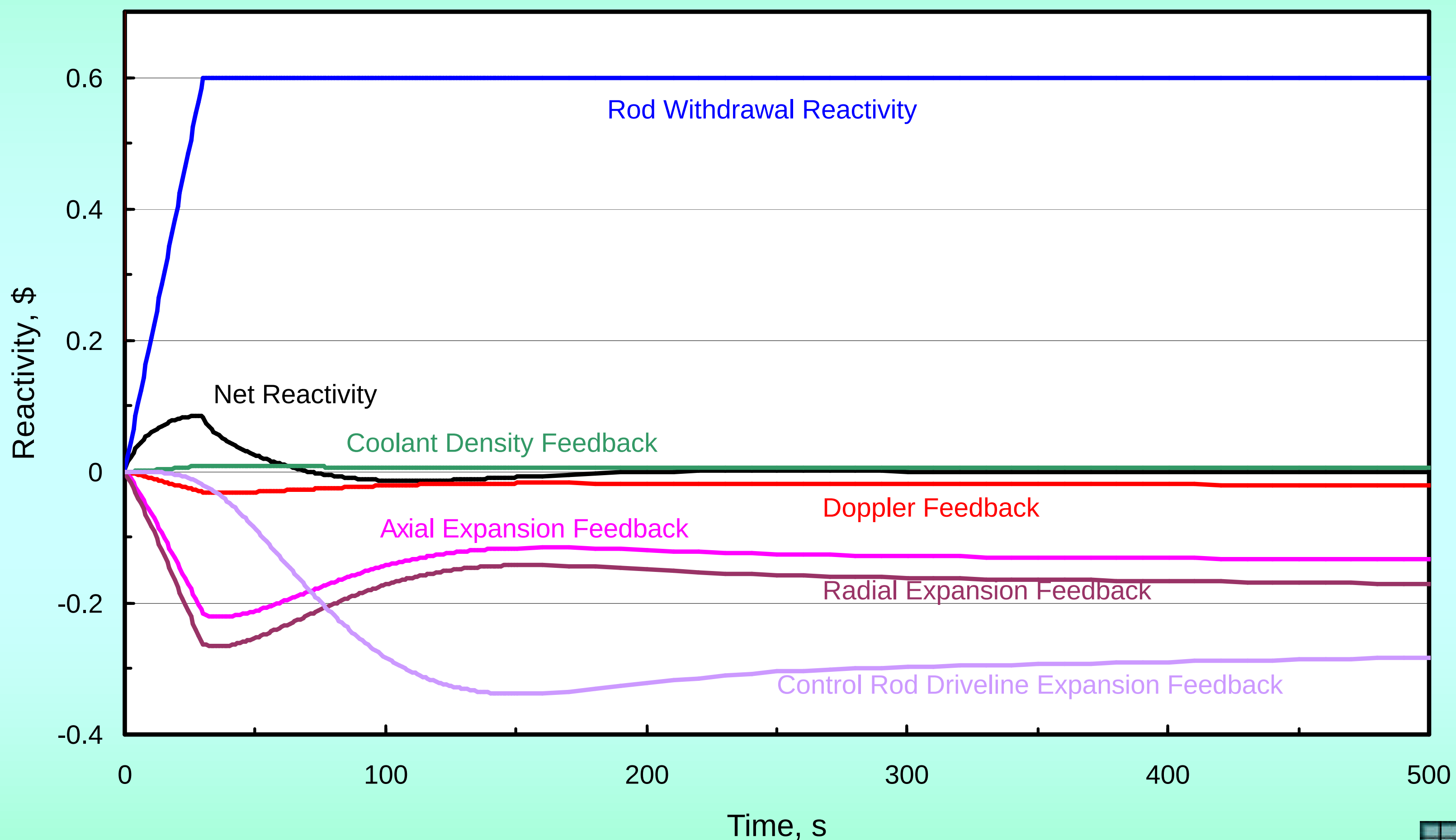
- **Support fraction much higher for fast reactor scenarios**
  - At CR~0.5, roughly twice capacity of CR=0 ADS systems required
- **However, different constraints were applied**
  - For FR, limited to conventional fuel enrichment
  - For ADS, nonuranium fuel form was employed
  - Prevailing wisdom is that fast reactor safety performance will be compromised at low uranium content
- **Low conversion ratio fast reactor design study - ANL**
  - How low can the uranium content be reduced without adverse consequences to reactor safety?
- **Advanced reactor/fuel technology options also considered**
  - Dedicated heavy metal (Pb-Bi) coolant burners – MIT
  - Utilization of Th-based fuel - UM

Low Conversion Ratio Burners: Performance Results

Fuel Enrichment, % TRU/HM	27/33	37/46	46/58	100
TRU Conversion Ratio	**0.47**	0.31	0.22	**0.00**
Net TRU consumption rate (kg/yr)	126	170	198	**270**
Burnup Swing (%Dk)	2.8	3.9	4.6	**6.4**
Sodium Void Worth ($)	2.2	1.5	0.53	-7.0
Radial Expansion Worth (cents/C)	-0.34	-0.40	-0.44	-0.57
Doppler Worth (cents/C)	-0.066	-0.060	-0.051	-0.011
Peak TOP Fuel Temperature, K	863	889	898	**944**
Peak LOHS Coolant Temperature, K	875	872	853	849

- **Conventional enrichment at CR ~ 0.5**
  - Enrichment gradually increases to roughly 50% TRU/HM at CR ~ 0.25
- **Burnup reactivity loss increases sharply at low CR**
- **High leakage configurations improve void worth and expansion coefficients**
- **Unprotected TOP, LOF, and LOHS events analyzed for whole-core**
  - Passive responses are effective in all cases – mild temperature increases
  - Largest temperature rise observed for TOP case at low CR

Sample Transient Result: Reactivity for TOP Event, CR=0.22



Advanced Fast Pb-Bi Cooled Reactors for Actinide Burning - MIT

Reactor Designs Being Explored

Fertile Free Fuelled TRU incinerator (ABR)

Dedicated Minor Actinide Burner with Thorium-based fuel (MABR)

Technical Challenges

Small b_{eff}, Doppler and coolant voiding reactivity feedbacks

Innovative Technical Solutions Adopted

a) Streaming Assemblies

b) Double-entry CRD system

Safety Features Comparable to IFR

Parameter	ABR	Th-MABR
A [¢]	-12.0	-7.1
B [¢]	-33.0	-21.8
C [¢/K]	-0.41	-0.24
A/B	0.37 [0:1.50]	0.33 [0:1.50]
$C D T/B$	1.24 [1:1.54]	1.08 [1:1.54]
$D r_{TOP} / \|B\|$	1.46 [0:1.50]	1.11 [0:1.50]

¤ TRU Destruction Rates

1. ABR ~ 0.38 [kg_{HM} / MWth / EFPYs] ~ 239 (192 Pu) [kg_{TRU} / yr]
2. MABR ~ 0.26 [kg_{TRU} / MWth / EFPYs] ~ 170 (125 MAs) [kg_{TRU} / yr]

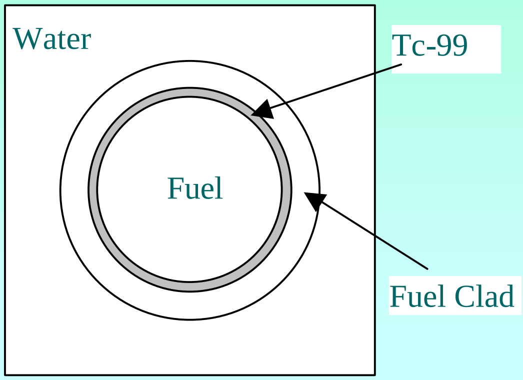
Potential Use of Thorium in Transmuters

- Th-U fuel increases Pu/TRU consumption.
  - ^{239}Pu reduction matched by ^{233}U production.
- Denatured with ^{238}U, fissile ^{233}U production may not increase proliferation risk.
- Results for typical burnup, 20% Th in fertile fuel.

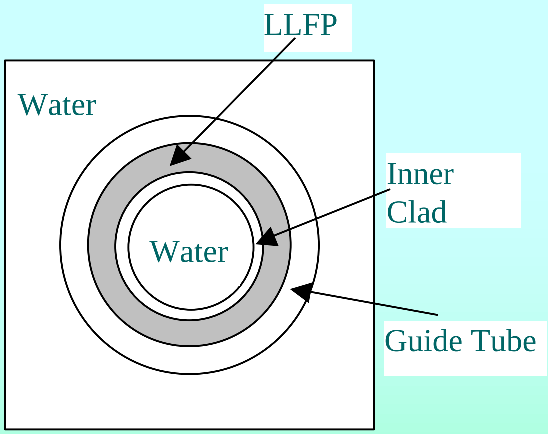
	LWR Spent Fuel Feed	
Transmuter Characteristics	U-TRU	Th-U-TRU
Enrichment (TRU/HM)	28%	29%
TRU feed (kg/yr)	588	599
U-233 production rate (kg/yr	0	16
Pu-239 destruction rate (kg/y	80	97
TRU destruction rate (kg/yr)	117	136

Long-Lived Fission Product (LLFP) Transmutation in Reactors

- Systematic evaluation of transmutation priorities
  - Tc-99 and I-129 identified
- Transmutation potential in both fast and thermal systems
  - Conventional PWR
  - Sodium-cooled ATW design
- Wide variety of target designs were considered in both systems
  - Also homogeneous with fuel
  - Moderated targets in FR
- Fuel cycle loading optimization studies performed
  - Number of targets/regional variations
  - Impact on key reactor performance parameters evaluated



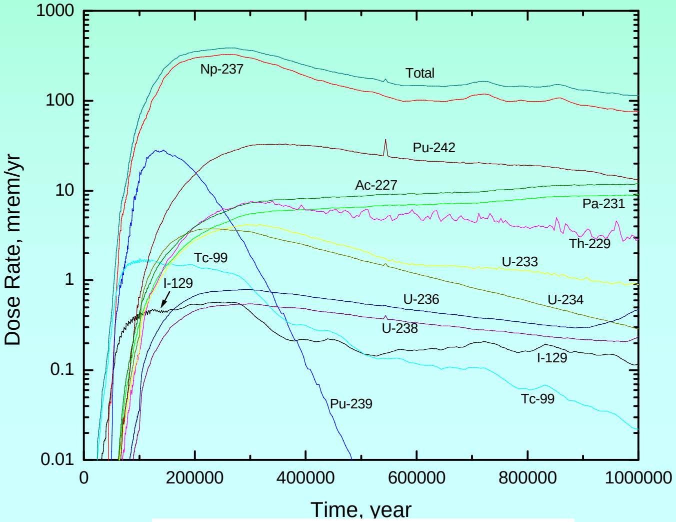
Tc-99-Coated Fuel Pellet



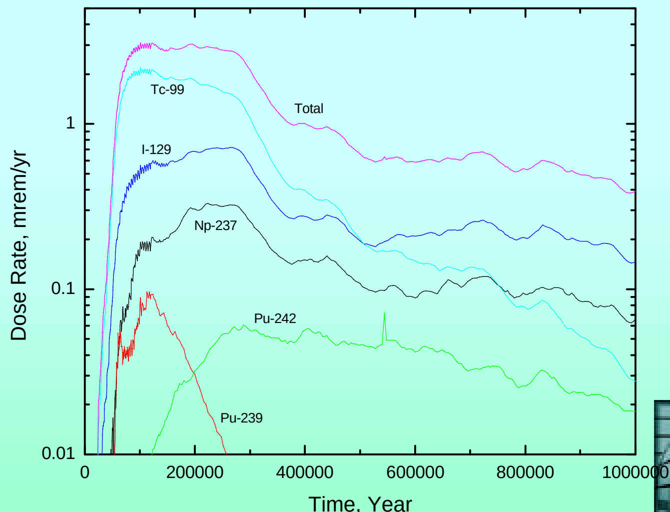
Annular Target in Guide Tube

Key Conclusions of LLFP Transmutation Studies

- Both Tc-99 and I-129 can be *stabilized* in same PWR core
  - Mix Tc-99 with fuel
  - Moderated CaI_2 targets in guide tubes
- Fast systems attractive because of excess neutrons
  - Preferred loading is moderated targets on core periphery
  - Net consumption can be achieved
- Impact on repository released dose rates was evaluated
  - LLFP dominate in short-term
  - More important with TRU elimination
  - Remain below regulatory limit
- Need for specialized waste form or LLFP transmutation not compelling



Direct Disposal of LWR Fuel



Disposal with TRU Transmutation

Summary of AFCI Systems Studies

- **Waste characteristics significantly improved by transmutation**
  - Removal of bulk uranium from high level waste
  - Reduction of key parameters (heat load, dose) by TRU destruction
  - Transmutation performance driven by processing loss fractions
- **Tier 1 can be effective for burning plutonium and reducing Tier 2 infrastructure**
  - Extent of burnup impacts Tier 2 system performance
- **A variety of LWR reactor options have been considered**
  - Heterogeneous loading, MOX, thorium, and nonfertile fuel forms
  - Multi-recycle of plutonium appears feasible
  - TRU multi-recycle limited by practical considerations
- **A variety of fast reactor options have been considered**
  - Low conversion ratio, heavy metal coolant, thorium fuel
  - High enrichment fuels offer a safe and viable alternative/complement to Tier 1 partial burning to reduce the Tier 2 infrastructure
- **Reactor transmutation of LLFP is possible**
  - Stabilize Tc-99 and I-129 in PWR, or burn in dedicated fast reactor